A Critical Test of Topological Defect Models: Spatial Clustering of Clusters of Galaxies

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ABSTRACT

Gaussian cosmological models, typified by the inflationary cold dark matter models, and non-Gaussian topological defect based cosmological models, such as the texture seeded model, differ in the origin of large-scale cosmic structures. In the former it is believed that peaks at appropriate scales in the initial high density field are the sites onto which matter accretes and collapses to form the present galaxies and clusters of galaxies, whereas in the latter these structures can form around the density perturbation seeds (which are textures in the texture model). Textures initially are randomly distributed on scales larger than their size, in sharp contrast to the initial high density peaks in the Gaussian models which are already strongly clustered before any gravitational evolution has occured. One thus expects that the resultant correlation of large cosmic objects such as clusters of galaxies in the texture model should be significantly weaker than its Gaussian counterpart.

We show that an $\Omega_0 = 1$ biased $b = 2$ (as required by cluster abundance observations) texture model (or any random seed model) predicts a two-point correlation length of $\leq 6.0h^{-1}$Mpc for rich clusters, independent of richness. On the other hand, the observed correlation length for rich clusters is $\geq 10.0h^{-1}$Mpc at an approximately 2σ confidence level. It thus appears that the global texture cosmological model or any random seed cosmological models are ruled out at a very high confidence ($> 3\sigma$).

Subject headings: Cosmology: large-scale structure of Universe – cosmology: theory – galaxies: clusters

1. Introduction

Cosmological models seeded by topological defects such as cosmic strings (Zel'dovich 1980; Vilenkin 1981,1985), global textures (Turok 1989) and global monopoles (Barriola & Vilenkin 1989; Bennett & Rhie 1990) have been proposed as an alternative to inflationary models, under the general gravitational instability paradigm of structure formation. Inflationary models such as the cold dark matter (CDM) models are Gaussian in the sense that the one-point density probability function is Gaussian distributed, generated by random quantum fluctuations in the early universe (Guth & Pi 1982; Albrecht & Steinhardt 1982; Hawking 1982; Linde 1982; Starobinsky 1982; Bardeen, Steinhardt & Turner 1983). In contrast, topological defect based models, taking the texture model as an example throughout this paper, are non-Gaussian and highly skewed. More importantly, it is thought that, in the Gaussian models, cosmic entities such as galaxies and clusters of galaxies form around high peaks in the initial density field, identifiable after smoothing the density field by a window of the size of the objects of interest. This structure formation scheme in Gaussian models, initially put forth by Kaiser (1984) to explain the enhanced Abell cluster correlation and named the "biased" structure formation mechanism, yields a clustering of clusters of galaxies substantially stronger than matter or galaxies (e.g., Peacock & Heavens 1985; Barnes et al. 1985; Bardeen et al. 1986; Martinez-Gonzalez & Sanz 1988; Frenk et al. 1990). On the other hand, the texture model (Turok 1989) predicts that textures, being the sites where galaxies or clusters of galaxies later form, are uncorrelated and randomly distributed *initially* on scales larger than their horizon size (Spergel et al. 1991), which in the case of clusters is about $10h^{-1}$Mpc. In this paper we relate this initial property of textures to the final spatial correlational properties of clusters of galaxies (Bahcall & Soneira 1983; Klypin & Kopylov 1983). We identify clusters of galaxies as a good tool because they are likely to be less affected than galaxies by non-gravitational processes. Consequently, calculations of their clustering properties under the gravitational instability scenario are

likely to be valid. In addition, the scales where the cluster-cluster correlation function is reliably measured observationally have not yet left the linear regime and therefore some simple linear theory relations may be employed. We show that the two-point cluster-cluster correlation length in the texture model is in the range $5.0 - 13.0h^{-1}$Mpc for an unbiased $b = 1$ model, and proportional approximately inversely to b. In comparison, the observed correlation length is $\geq 10h^{-1}$Mpc (at an approximately 2σ level). Since observations of rich cluster abundance independently require that $b \approx 2$ for $\Omega_0 = 1$ (the cosmological mean density in units of the critical density) inflationary models (Bahcall & Cen 1992; White et al. 1993; Viana & Liddle 1995; Eke, Cole, & Frenk 1996), $b > 2$ is necessary for the corresponding non-Gaussian (positively skewed) models in order not to overproduce the abundance of rich clusters of galaxies. We therefore conclude that the texture model, or any random (or weakly correlated) seed cosmological models *per se*, is ruled out at a very high confidence level ($> 3\sigma$). For a related, very comprehensive study of non-Gaussian as well Gaussian models using a suite of well defined statistical measures, see Weinberg & Cole (1992).

This paper is organized as follows. In the next section we give an analytic technique to compute the evolution of the correlation function for any set of objects and apply it to the specific case of clusters of galaxies in the texture model. Conclusions are given in §3.

2. Cluster Correlation Computed by an Analytic Technique

The approach adopted here to calculate the cluster-cluster two-point correlation function in the texture model is conceptually very simple, as follows. Barring merging, the temporal evolution of the two-point correlation function of any set of objects, ξ, is governed

by the pair conservation equation (equation 71.6 of Peebles 1980):

$$\frac{\partial \xi}{\partial t} + \frac{1}{x^2 a}\frac{\partial}{\partial x}\left[x^2(1+\xi)v\right] = 0 \quad , \tag{1}$$

where t is time; a is the expansion parameter; x is the comoving separation; and v is the mean pairwise proper peculiar velocity. Our subsequent results are directly or indirectly based on this equation. Note that equation (1) is valid for *any set of objects*. We will first derive a relation between pairwise peculiar velocity and correlation function of the matter in the linear regime, using equation (1). Following Subramanian & Padmanahban (1994), substituting the conventional two-point matter correlation function ξ_m with $\bar{\xi}_m$, the volume-averaged two-point correlation of the *underlying matter* within a sphere of radius x, defined by

$$\bar{\xi}_m(x,t) \equiv \frac{3}{x^3}\int_0^x \xi_m(y,t) y^2 dy \quad , \tag{2}$$

we may obtain a slightly different form for equation (1) as:

$$\left(\frac{\partial}{\partial \ln a} - h\frac{\partial}{\partial \ln x}\right)(1+\bar{\xi}_m) = 3h(1+\bar{\xi}_m) \quad , \tag{3}$$

where $h \equiv v/(-\dot{a}x)$. Note that v is negative when pairs approach. Equation (3) is obtained by substituting equation (2) into equation (1) and by integrating it once with respect to x. An integration constant on the right hand side of equation (3) has been set to zero in order to produce the right asymptotic behavior: ξ_m freezes out in comoving space when $h = 0$. In the linear limit, where the peculiar velocity is much smaller than the Hubble velocity (i.e., $h << 1$) and $\bar{\xi}_m \propto (1+z)^{-2}$ (for an $\Omega_0 = 1$ universe, which is assumed throughout and consistent with the texture model where $\Omega_0 = 1$ is usually assumed; we note that this linear growth rate of matter correlation is in agreement with detailed numerical simulations of Cen et al. 1991 and Park, Spergel, & Turok 1991), the only nontrivial solution is

$$v(x,t) = \frac{2}{3}\bar{\xi}_m v_H \quad , \tag{4}$$

where $v_H = \dot{a}x$ is the Hubble velocity for separation x at time t.

Equation (4) allows us to obtain the evolution of the total matter pairwise motion, $v(x,t)$, from $\bar{\xi}_m$, which in turn is constrained by the observed galaxy-galaxy two-point correlation function. For the linear scales which we are interested in, namely $\geq 10h^{-1}$Mpc, where density fluctuations at all epochs are in the linear regime, we assume the following form:

$$\xi_m(x,z) = \left(\frac{x}{x_{gg,0}}\right)^{-\gamma} \frac{1}{(1+z)^2}\frac{1}{b^2} \quad , \tag{5}$$

where $x_{gg,0}$ is the galaxy-galaxy correlation length at $z=0$; $b \equiv \frac{\sigma_{gal,rms}}{\sigma_{m,rms}}$ is the (linear) bias factor; and we have changed the time variable from t to redshift z. Combining equations (2,4,5) we obtain the *mean comoving* pairwise velocity of total matter (similar to equation 71.13 of Peebles 1980), $v_{mc} \equiv v(1+z)$:

$$v_{mc}(x,z) = \frac{2}{3-\gamma}\frac{H_0 x_{gg,0}}{b^2}\left(\frac{x}{x_{gg,0}}\right)^{-\gamma+1}(1+z)^{-1/2} \quad , \tag{6}$$

where H_0 is the present Hubble constant and we have made use of the relation $H(z) = H_0(1+z)^{3/2}$ for the $\Omega_0 = 1$ cosmology.

Equation (6) describes the evolution of the *mean comoving* pairwise velocity of *total matter* in the *linear regime*, constrained by the observed galaxy-galaxy correlation function and linear theory. We now make a critical observation that a subset of objects, for example, cluster-scale textures, can have *different* v_{mc} from that of total matter. It would not be hard to imagine cases where such situations could arise. For instance, in defect models where density fluctuations are produced by initial density and/or velocity kicks, both decaying and growing modes exist, whereas equation (6) describes only the growing mode of the overall matter perturbation under the self-gravitational action of the matter itself. While detailed dynamics of textures and the induced matter perturbations are very complicated and require nonlinear numerical calculations, we argue that there is a maximal v_{mc} for any random set of objects within the gravitational instability framework. Two examples should demonstrate the relevant possible cases. In the first example, if the perturbation seeds are

densely populated in redshift, one may obtain the time-averaged peculiar velocity at any epoch as

$$v_{mc,dense}(z_f) \equiv \frac{\int_{t_f}^{\infty} v_{mc}(z_f)(1+z)/(1+z_f)dt}{\int_{z_f}^{\infty} dt} = 3v_{mc}(z_f) \quad , \tag{7}$$

where the second equality is obtained by inserting $t \propto (1+z)^{-3/2}$ and v_{mc} is given by equation (6). In the second example, if the perturbation seeds are sparsely created in redshift, one then has the time-averaged peculiar velocity at any epoch as

$$v_{mc,sparse}(z_f) \equiv \frac{\int_{t_f}^{\infty} v_{mc}(z_f)(1+z)/(1+z_f)dt}{\int_{z_f}^{\infty}(1+z_f)^{3/2}/(1+z)^{3/2}dt} = 6v_{mc}(z_f) \quad . \tag{8}$$

The denominator in equation (8) becomes apparent by noting that $v_{mc} \propto (1+z)^{-3/2}$ (v is the proper pairwise velocity), indicated by equations (4,5). In both cases (equations 7,8), we have maximized the velocity by assuming that the initial velocity (kick) is just let decay as $\propto (1+z)$ due to the universal expansion. One may think of $v_{mc,dense}$ or $v_{mc,sparse}$ as the envelope wrapping a set of decaying velocity modes in redshift, which are seamed onto the general matter velocity evolution (growing mode) when the decaying velocity is just about to fall below the growing velocity. Such decaying modes can be created, for example, by velocity kicks due to the unwinding of ever larger (when time progresses) textures in the expanding universe, up to the present (Spergel et al. 1991).

A critical assumption has just been made here and is worth being elaborated more. That is, the velocity of these considered objects, while allowed to be different from that of the matter for periods of time, is demanded to be synchronized with that of overall matter at some intermittent points. This is equivalent to saying that, while perturbation seeds (whose occurrences may not be limited to certain time intervals) create the initial perturbations, the subsequent evolution of perturbed matter density/velocity fields is determined by the gravitational instability of the matter itself (i.e., self-gravity of the matter). However, if perturbation seeds not only initiate the perturbations but also dominate the subsequent evolution, our assumption breaks down. But such extreme cases would not fit into the

gravitational instability picture which we are considering here; i.e., such cases are likely to have some other grossly different properties than those encountered in the gravitational instability framework. In any case, it seems that all proposed seed models, including those based on topological defects or other, (perhaps) more conventional seeds such as primordial black holes (e.g., Villumsen, Scherrer, & Bertschinger 1991), do not have such dominant perturbation seeds, at least on the scales which we are investigating here ($x \geq 10h^{-1}$Mpc). We therefore argue that the pairwise velocity given in equation (8) constitutes the upper limit of possible values for any set of selected objects within the general gravitational instability framework. In the specific case of the texture model, the textures are relatively rare, as indicated by the texture evolution results (Spergel et al. 1991), $dn/d\eta = \nu/\eta^4$ with $\nu \sim 0.02$ and n being the number density of textures created per unit comoving volume (η is the conformal time). This implies that the correlation function of clusters in the texture model should be more appropriately upper limited by that derived using the velocity field given by equation (8), as will be shown below.

We note that, while equation (1) is valid for any set of objects, Equation (4) may not hold for them even at large scales where v is small compared to the Hubble velocity (i.e., $h << 1$). The reason is that equation (4) was derived in the limit where both $\bar{\xi} << 1$ and $h << 1$. But the correlation of clusters of galaxies under consideration here is supposedly significantly higher than that of matter thus may not be much less unity. As a result, we can not directly convert v into ξ using equation (4) for the objects under our consideration, rather we need to solve equation (1) directly by providing $v(x,t)$. Although it is straightforward to solve equation (1) to get ξ given v, we find the following method (basically a Lagrangian integral form of equation 1) conceptually simple to work with to derive the evolution of ξ. Let us write down the usual form (definition) of ξ at any epoch:

$$\xi(x) = \frac{N_p}{4\pi x^2 \Delta x n} - 1 \quad , \tag{9}$$

where N_p is the number of pairs within a shell of width Δx located x from an object in question; n is the number density of the objects of interest. In the absence of shell crossing of pairs, which holds for the form of v_{mc} as given in equation (6), we can relate the final correlation to the initial correlaton by

$$\xi_f(x_f) = \frac{x_i^2}{x_f^2}\frac{dx_i}{dx_f}[\xi_i(x_i)+1]-1 \quad , \tag{10}$$

where x_i and x_f are the initial and final separations (bins) of pairs under consideration, respectively. Therefore, all that we need to do is to solve the evolution of x, which is very simple to follow. What is yet left to be specified is the initial correlation function of textures, $\xi_i(x)$. Spergel et al. (1991) have shown that textures are initially uncorrelated (randomly distributed) on scales larger than their horizon size. For textures which we are interested in here, their horizon size is about $10h^{-1}$Mpc, giving a mass of $\sim 10^{15}h^{-1}M_\odot$. Therefore, there is no clustering of cluster-size textures on scales $\geq 10h^{-1}$Mpc *initially*, the range over which we wish to compute the evolution of clustering of these textures; i.e., $\xi_i(x) = 0$ at $x > 10h^{-1}$Mpc. A related point, the majority of these textures are produced at times slightly before the epoch of matter radiation equality at redshift $z \sim 10^4$ in the texture model (Gooding, Spergel, & Turok 1991).

Integrating $\frac{dx}{dt} = v_{mc}$, where v_{mc} is given by Equation (7) or (8), with the initial condition $\xi_i(x) = 0$ at z_i (the starting redshift of pairwise movement, presumably the birth redshift of the relevant textures at $z_i \sim 10^4$) give the correlation function of the clusters at redshift z:

$$\xi(x,z) = (1+\frac{y}{x^\gamma})^{\frac{3}{\gamma}-1}-1 \quad , \tag{11}$$

where

$$y = \frac{\alpha\gamma}{3-\gamma}x_{gg,0}^\gamma\frac{1}{b^2}\left[\frac{1}{(1+z)^2}-\frac{1}{(1+z_i)^2}\right]. \tag{12}$$

Setting ξ to be unity (and $z_i = \infty$) we can find the cluster-cluster correlation length at

$z = 0$

$$r_{cc,0} = x_{gg,0} \left[\frac{\alpha\gamma}{(3-\gamma)(2^{\frac{\gamma}{3-\gamma}} - 1)} \right]^{1/\gamma} b^{-2/\gamma} \quad , \tag{13}$$

where α is 3 and 6, respectively, for the two cases indicated by equations (7) and (8). The results shown in Figure 1, the corrlation length of clusters as a function of bias parameter b, are computed using equation (13) with the canonical observed values for galaxies (Davis & Geller 1976) of $\gamma = 1.8$ and $r_{gg,0} = 5.0h^{-1}$Mpc. Three cases are shown for three values of α: 1 corresponds to matter correlation (heavy solid curve), 3 corresponds to the upper limit in the case of densely populated seeds in redshift space (heavy long dashed curve), and 6 corresponds to the upper limit in the case of sparsely populated seeds in redshift space (heavy short dashed curve), which we argue is the absolute upper limit. Also shown in Figure 1 are the corresponding cases with $\gamma = 1.0$ to illustrate the dependence of the correlation length on γ, the slope of the correlation function. We note that, in the derivation of $r_{cc,0}$, no assumption about the cluster number density is made, except the very weak dependence of the calculation on z_i due to different birth redshift of seeds for different mass clusters. This implies that the cluster correlation length in the texture model, or any other seed model of that sort, is richness independent.

We see that the cluster-cluster two-point correlation length should be in the range $r_{cc,0} = 5.0 - 13.0h^{-1}$Mpc (between heavy solid and short dashed curves) for an unbiased $b = 1$ model, and decreases with increasing bias parameter. This correlation length range for the $b = 1$ model is consistent with the results obtained from N-body simulations by Park, Spergel, & Turok (1991), who find a correlation length of $\sim 9.0 \pm 3.0h^{-1}$Mpc (adapted from Figure 3 of Park et al. 1991) for the $b = 1$ model. This agreement lends support for the validity of this analytic approach, and perhaps explains the origin of cluster-cluster correlation in the texture model. Another way to explain the origin is this. The correlation of clusters of galaxies, whose seeds are produced without any mutual correlation initially at high redshift near matter radiation equality in the textures model, grows gradually with

time due to density perturbations on larger scales induced by larger textures which unwind at subsequent times up to the present.

Observations of galaxy cluster abundance indicate that the bias parameter $b \sim 2$ for $\Omega_0 = 1$ inflationary Gaussian models (Bahcall & Cen 1992; White et al. 1993; Viana & Liddle 1995; Eke, Cole, & Frenk 1996). The required bias parameter in non-Gaussian (positively skewed) models is even larger due precisely to the non-Gaussianity, which enables collapse of overdense regions easier. We hence see that, for a viable defect model with $b > 2$ and $\Omega_0 = 1$, the cluster-cluster correlation function length should be smaller than $r_{cc,0} = 6.0h^{-1}$Mpc (obtained for $b = 2$ models). The depedence on γ is weak at $b \geq 2$ as seen in Figure 1: for the extreme case with $\gamma = 1.0$, $r_{cc,0} = 2.0 - 9.0h^{-1}$Mpc for $b = 2$ models. The range in $r_{cc,0}$ is due to the possible range in α.

Postman, Huchra, & Geller (1992) give $r_{cc,0} = 20.0 \pm 4.3h^{-1}$Mpc using a complete sample of 361 Abell clusters. Nichol et al. (1992) present $r_{cc,0} = 16.4 \pm 4.0h^{-1}$Mpc for a 90 percent complete sample of 97 clusters from the Edinburgh-Durham Southern Galaxy Catalogue. Dalton et al. (1992) yield $r_{cc,0} = 12.9 \pm 1.4h^{-1}$Mpc for 173 clusters from APM galaxy survey and $r_{cc,0} = 14.0 \pm 4.0h^{-1}$Mpc for the 93 richest clusters in the sample. Dalton et al. (1994) conclude that $r_{cc,0} = 14.3 \pm 2.4h^{-1}$Mpc ($2\sigma$) for 364 clusters from an extended APM galaxy survey. Romer et al. (1994) indicate $r_{cc,0} = 13 - 15h^{-1}$Mpc for a ROSAT X-ray selected cluster sample of 128 clusters. Croft et al. (1997) find $r_{cc,0} = 21.3^{+11.1}_{-9.3}h^{-1}$Mpc ($2\sigma$) for clusters with a mean space density of $1.6 \times 10^{-6}h^3$Mpc^{-3}, equivalent to the space density of Abell richness ≥ 2 clusters, by analysing a new catalogue of very rich clusters selected from APM galaxy survey. While uncertainties remain in the current clustering analyses of observed clusters due to still limited cluster samples of order of a few hundred clusters at most, it seems that all these studies have consistently given a correlation length $\geq 10h^{-1}$Mpc at approximately 2σ level with average errorbar of size of $2 - 4$ h^{-1}Mpc. We

therefore conclude that $b \geq 2$ texture models can be ruled out at a very high confidence level ($> 3\sigma$).

3. Conclusions

Based on simple analytic reasoning within the gravitational instability framework, we are able to set an upper limit on the correlation length of clusters of galaxies in any *random* seed cosmological model, regardless of the nature of the seeds, which could be topological defects such as textures or more conventional seeds such as primordial black holes. It is shown that clusters of galaxies in any biased $b = 2$ model has a two-point correlation length of $r_{cc,0} \leq 6.0h^{-1}$Mpc (for a slope of the correlation function of -1.8). More likely, one is forced to adopt a bias parameter $b < 2$ for such non-Gaussian (positively skewed) models as not to overproduce the abundance of rich clusters of galaxies observed locally, since it is easier to form overdense structures with non-Gaussian positively skewed density perturbations. All recent observations indicate a correlation length $r_{cc,0} > 10.0h^{-1}$Mpc at an approximately 2σ level for real rich clusters of galaxies (with a typical errorbar size of $2 - 4\ h^{-1}$Mpc). It is thus apparent that any topological defect models or any random seed models are ruled out at a very high confidence level ($> 3\sigma$).

While this constraint is completely independent of observations on any other scales including those of the CMB, the requirement of a large $b \sim 4$ in order to fit the observed angular power of CMB on very large scales for the global texture model (Pen et al. 1997), for example, would render the model inviable in terms of matching the observed correlation of rich galaxy clusters.

An unbiased $b = 1$ topological defect model might be able to provide a reasonable match to the observed cluster correlation. One way to achieve this is to adopt a lower

density model with $\Omega_0 = 0.2 - 0.3$ (with or without a cosmological constant Λ). But such a model might have more difficulty in fitting the large scale CMB observations. In addition, such a model (especially in the case with zero Λ) might run into the opposite of a problem that inflationary cold dark matter models have: too early structure formation. This deserves more careful calculations, should such a model be put forth.

Another exit is to have the perturbations seeds responsible for the formation of clusters of galaxies at later times significantly clustered at birth before any gravitational evolution, somewhat analagous to high density peaks in Gaussian models. This might be an attractive route to search for potentially viable seed models, especially those based on topological defects.

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REFERENCES

Albrecht, A. & Steinhardt, P.J. 1982, Phys. Rev. Lett., 48, 1220

Bahcall, N.A., & Cen, R. 1992, ApJ, 407, L49

Bahcall, N.A., & Soneira, R.M., 1983, ApJ, 270, 20

Bardeen, J.M., Steinhardt, P.J., & Turner, M.S. 1983, Phys. Rev. D, 28, 679

Bardeen, J.M., Bond, J.R., Kaiser, M., and Szalay, A.S. 1986, ApJ, 304, 15

Barnes, J., Dekel, A., Efstathiou, G., & Frenk, C.S. 1985, ApJ, 295, 368

Barriola, M. & Vilenkin, A. 1989, Phys. Rev. Lett., 63, 341

Bennett, D.P., & Rhie, S.H. 1990, Phys. Rev. Lett., 65, 1709

Cen, R., Ostriker, J.P., Spergel, D.N., & Turok, N. 1991, ApJ, 383, 1

Croft, R.A.C., Dalton, G.B., Efstathiou, G., Sutherland, W.J., & Maddox, S.J. 1997, preprint, astro-ph/9701040

Dalton, G.B., Efstathiou, G., Maddox, S.J., & Sutherland, W.J. 1992, ApJ, 390, L1

Dalton, G.B., Croft, R.A.C., Efstathiou, G., Sutherland, W.J., Maddox, S.J., & Davis, M. 1994, MNRAS, 271, L47

Davis, M., & Geller, M.J. 1976, ApJ, 208, 13

Eke, V.R., Cole, S., & Frenk, C.S. 1996, preprint

Frenk, C.S., White, S.D.M., Efstathiou, G., & Davis, M. 1990, ApJ, 351, 10

Gooding, A.K., Spergel, D.N., Turok, N. 1991, ApJ, 372, L5

Guth, A.H., & Pi, S.-Y., 1982, Phys. Rev. Lett. 49, 1110

Hawking, S.W. 1982, Phys. Lett. B, 115, 295

Kaiser, N. 1984, ApJ, 284, L9

Klypin, A.A., & Kopylov, A.I. 1983, Soviet Astr. Letters, 9, 41

Linde, A. 1982, Phys. Lett, 108B

Martinez-Gonzalez, E., & Sanz, J.L., 1988, ApJ, 324, 653

Nichol, R.C., Collins, C.A., Guzzo, L., & Lumsden, S.L. 1992, MNRAS, 255, 21p

Park, C., Spergel, D.N., & Turok, N. 1991, ApJ, 372, L53

Peacock, J.A., & Heavens, A.F. 1985, MNRAS, 217, 805

Peebles, P.J.E. 1980, "The Large-Scale Structure of the Universe" (Princeton: Princeton University Press)

Pen, U., Seljak, U., & Turok, N. 1997, preprint, astro-ph/9704165

Postman, M., Huchra, J.P., & Geller, M.J. 1992, ApJ, 384, 404

Romer, A.K., Collins, C.A., Bohringer, H.,Cruddace, R.G., Ebeling, H., MacGillivray, H.T., & Voges, W. 1994, Nature, 372, 75

Spergel, D.N., Turok, N., Press, W.H., & Ryden, B.S. 1991, Phys. Rev. D, 43, 1038

Starobinsky, A.A. 1982, Phys. Lett, 117, 175

Subramanian, K., & Padmanabhan, T. 1994, MNRAS, 271, 976

Turok, N. 1989, Phys. Rev. Lett., 63, 2625

Viana, P.T.P, & Liddle, A.R. 1995, preprint

Vilenkin, A. 1981, Phys. Rev. Lett., 46, 1169

Vilenkin, A. 1981, Phys. Rep., 121, 263

Villumsen, J., Scherrer, R.J., Bertschinger, E. 1991, ApJ, 367, 37

West, M.J., & van den Bergh 1991, ApJ, 371, 1

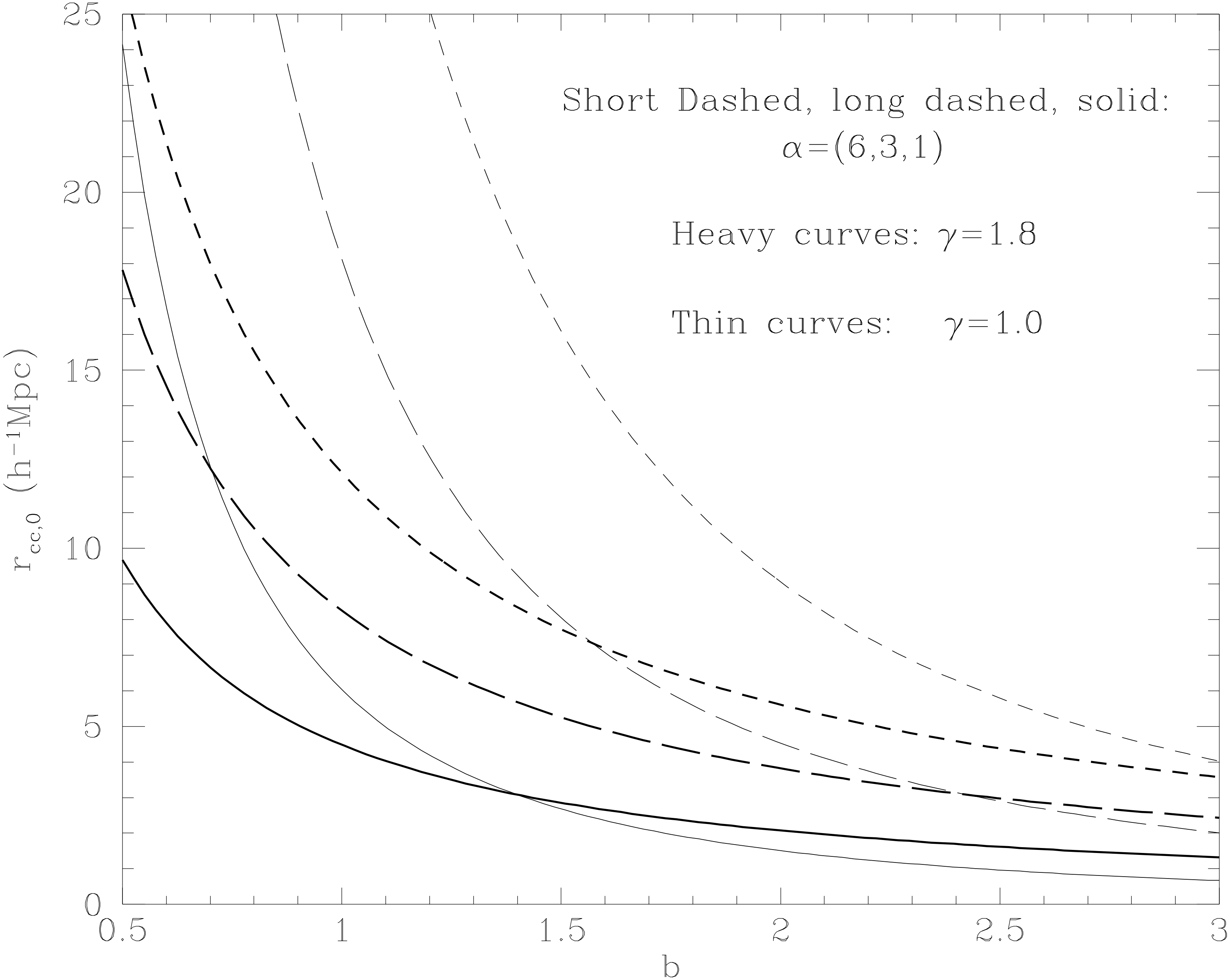
Weinberg, D.H., & Cole, S. 1992, MNRAS, 259, 652

White, S.D.M., Efstathiou, G., & Frenk, C.S. 1993, MNRAS, 262, 1023

Zel'dovich, Ya. B. 1980, MNRAS, 192, 663

Fig. 1.— Cluster-cluster two-point correlation length as a function of bias factor b, using equation (13) with the canonical observed values for galaxies (Davis & Geller 1976) of $\gamma = 1.8$ and $r_{gg,0} = 5.0$. Three cases are shown for three values of α: 1 corresponds to matter correlation (heavy solid curve), 3 corresponds to the upper limit in the case of densely populated seeds in redshift space (heavy long dashed curve), and 6 corresponds to the upper limit in the case of sparsely populated seeds in redshift space (heavy short dashed curve). Also shown in Figure 1 are the corresponding cases with $\gamma = 1.0$ to illustrate the dependence of the correlation length on γ, the slope of the correlation function.

Figure 1


Short Dashed, long dashed, solid:
α=(6,3,1)
Heavy curves: γ=1.8
Thin curves: γ=1.0
25
20
15
10
5
0
0.5
1
1.5
2
2.5
3
b
r_cc,0 (h^-1Mpc)